AN EXPERIMENTAL INVESTIGATION OF THE VORTEX BREAKDOWN PHENOMENON IN A DIVERGING TUBE

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THESIS

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ABSTRACT

The vortex breakdown phenomenon was investigated, through the use of flow visualization techniques, over a wide range of flow conditions in terms of the circulation number and the Reynolds number.

The test section of the apparatus was, basically, a 10-inch diverging tube whose inside diameter was changed uniformly from 1.5 inches to 2.0 inches. The swirling flow was generated by introducing water through an arrangement of 32, radially located, streamlined vanes. The vortex breakdown position was recorded for different values of both the circulation number and the Reynolds number.

The results of the investigation have shown that the vortex breakdown may occur either in spiral or axisymmetric form (followed by a thicker core, then a spiral breakdown) and finally by turbulent mixing. The character of the structural change, as well as the position of the breakdown along the tube, are highly dependent on the circulation number and the Reynolds number. The existence of both types of breakdowns at well defined flow conditions shows that neither one is a consequence of instability in the other. The phenomenon appears to be a manifestation of critical conditions rather than flow instabilities.

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NOMENCLATURE

b	half distance between pivot points of adjacent vanes
D_o	diameter at the entrance of the diverging tube
H	height of vane
l	distance between the trailing edge and the pivot point of each vane
Q	flow rate
Q_m	maximum flow rate
R	radius of the circular locus of the pivot points
Re	Reynolds number
U	uniform axial velocity at the entrance of the diverging tube
V_1'	flow velocity parallel to the passage between vanes
z	distance normal to the passage between adjacent vanes
W	circulation number
α	half of the angle subtending the arc between adjacent pivot points; half angle of the body of each vane
Γ	circulation
γ	angle defined in Figure 3
δ	angle defined in Figure 3
η	angle at the trailing edge of each vane (see Figure 3)
θ	angle defined in Figure 3
ν	kinematic viscosity
π	3.1415927......
ρ	angle defined in Figure 3
σ	multiplication factor

τ angle defined in Figure 3

ϕ vane angle

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I. INTRODUCTION

The vortex breakdown or vortex bursting is a flow phenomenon which consists, esentially, of the abrupt change of the flow structure in the core of a swirling flow. The phenomenon has been observed in the vortex generated by flow separation from the leading edge of a surface with high sweep-back, such as a lifting delta wing. It has also been observed in swirling flow in pipes. The main characteristic of the breakdown is a sudden deceleration of the vortex core at some position along the axis of the vortex followed by a complex structural change.

Two basic types of breakdown have been observed. In one of them the axial core deforms into a spiral in which the rotational component of velocity has the same direction as the undisturbed flow. The other type of breakdown is the formation of an almost axisymmetric egg-shaped structure which presents an inner core of reversed flow. In both cases the flow becomes turbulent at some distance downstream of breakdown. Recently, a third type of breakdown has been reported by McHugh (1). It is described by him as a double helix pattern resulting from the division of the core axis into two branches, each of which was like a separate rotating core.

The vortex breakdown was discovered by Peckham and Atkinson in 1957 (2). Subsequently, several investigators have tried to discover its causes. Lambourne and Bryer (3) observed the bursting process for low speed flow over a flat-plate delta having 65 degrees sweep back. Their experiments were performed in a water tunnel. They were able to observe, with dye injection, both the spiral and the axisymmetric forms of breakdown. They also performed experiments in a wind tunnel using a variable-sweep flat-plate wing. In this case, the water-vapor condensation trail was used to visualize the position of breakdown over the surface. The burst position was found to be influenced by incidence and sweep-back. At high incidence, low angle of sweep, or a combination of both, the breakdown moved very close to the leading apex of the wing. It was suggested that a low total pressure at the axis of the vortex core was essential for the ocurrence of the breakdown. They stated that stagnation of the flow at the burst position was due to a positive gradient of static pressure along the vortex axis. The position of the phenomenon was found to be influenced neither by Reynolds number (in relation to the geometry of the wing) nor by small perturbations of the flow upstream of breakdown.

Later, Lambourne (4) continued the investigation of the phenomenon, the flow now being confined to a circular tube. From his observations, he suggested that the periodic spiral form of breakdown was originated from an instability of the axisymmetric form. He studied also, theoretically, the effect of an imposed pressure gradient on the vortex core. The theoretical calculations showed the possibility of an inner core of reversed flow existing due to the adverse pressure gradient. Lambourne concluded that there must be a critical value for a vortex to become unstable. This value was determined as $V/U = 1.2$, where V was the rotational component of velocity at the edge of the vortex core; U being the uniform longitudinal component of velocity within the core. However, he offered no suggestions about the type of structural change which must occur within the vortex as a consequence of instability.

A theoretical study of the phenomenon was performed by Squire (5). He suggested that breakdown might occur when the flow could sustain infinitesimal standing waves. He considered that, if such waves could exist, disturbances far downstream could spread upstream and hence cause the breakdown. He also suggested that a critical value of the tangent of the swirl angle, i.e. the ratio V/U, might exist, the value of which is between 1.0 and 1.2. Brooke Benjamin (6), objected to Squire's theory in part on the grounds that if the velocity of the standing waves was directed downstream (as stated by Squire), the waves could only form in the rear of a disturbing agency and could not spread upstream.

Benjamin's theory (6), (7), (8), proposed that vortex breakdown was a phenomenon analogous to hydraulic jump in open-channel flow. He considered the breakdown as a transition from a uniform state of swirling flow to one where stationary waves of finite amplitude were present. He found the solutions to the equations of potential motion by means of a perturbation analysis and using certain theorems in the calculus of variations. However, as Benjamin stated in (8), "... this explanation for vortex breakdown is handicapped by the complicated incidental effects that often appear experimentally...". He also suggested that his theory described the basic state upon which the actual flow subsisted.

His deductions that the subcritical conjugate flow can support standing waves of small amplitude and that it possesses a larger flow force (momentum flux) have been proved by Fraenkel (9) using a different method of approach. The hydraulic jump analogy is also supported by Sarpkaya (10). His studies showed that an abrupt change of structure was generated in swirling flow by the action of another vortex rotating in the opposite direction. In this case, the counter-vortex could be compared to the obstruction which is necessary in a channel to precipitate the hydraulic jump on a supercritical stream.

The theory developed by Benjamin supported, in part, Harvey's experimental studies (11). He observed the breakdown produced in a vortex tube. His studies concerned primarily with the axisymmetric form of breakdown. Harvey found that the original vortex motion was restored at the tail end of the stagnant bubble and a second breakdown (not clearly identifiable) was observed a short distance downstream. The fact that the flow downstream of the first breakdown had the same characteristics as the upstream flow lead Harvey to conclude that breakdown was a critical phenomenon, rather than a manifestation of instability. The critical condition was explained by considering the vortex burst as a division between supercritical and subcritical flow. The swirl angle distribution was also measured by Harvey. He found the value of the maximum angle to be in accordance with Squire's prediction for the value at which breakdown occurred.

Kirkpatrick (12), experimenting with a vortex tube, found that the total pressure decreased to a very low value near the axis of the vortex core. He measured the pressure distribution along the wall of the tube, finding a positive pressure gradient upstream of the breakdown and a negative gradient downstream. It was noticed that these gradients occurred only when breakdown was present.

A theoretical and experimental study was performed by Fantin (13) regarding the effect of an imposed pressure gradient on the vortex core. His conclusion that an imposed change beyond a critical value would lead to an unspecified change in flow structure agreed with Lambourne's conclusion (4). He found that standing waves would arise from the breakdown, which leads again to the hydraulic jump analogy.

Hall (14), based on the proposal of Lambourne and Bryer regarding the flow upstream of breakdown as quasi-cylindrical, suggested that the phenomenon might be treated as a failure of the quasi-cylindrical approximation. He used a numerical method to calculate the occurrence of failure and concluded that both the criteria of Squire and Benjamin could be used for the same purpose. Hence, he suggested that there might be a close relationship between breakdown and failure in a quasi-cylindrical flow. His study, however, was applicable only to the axisymmetric type of breakdown.

An experimental study of the temporal periodic motion that occurs in the vortex whistle and the cyclone separator was performed by Chanaud (15). He compared the results of this study with the vortex breakdown phenomenon. He suggested that the flow behavior in breakdown was very similar to that of vortex whistle and cyclone separator, where the flow is hydrodynamically unstable within a region of reversed flow on the swirl axis.

From the above discussion, it follows that the general trend has been to explain the occurrence of the breakdown in terms of either one of two phenomena, spiral instabilities or finite transitions between two conjugate states of flow. These and other uncertainties regarding the occurrence of vortex breakdown clearly demanded further investigation of the phenomenon.

The experiments described herein consisted of the observations of vortex breakdown through flow visualization techniques and the determination of the location of breakdown in terms of relevant parameters. The test section of the experimental apparatus was a 10-inch diverging tube. The inner diameter of the tube was uniformly increased from 1.5 inches at the entrance to 2.0 inches at the outlet. Obviously, the study of vortex motion in a tube is less complicated than that of a leading edge vortex. Whereas the vortex in a tube decays with distance, the leading edge vortex increases its strength due to the continuous feeding of vorticity to the vortex core.

The results of the present investigation have shown that the vortex breakdown may come about either in spiral or axisymmetric form (followed by a thicker core, then a spiral breakdown, and finally by turbulent mixing). The character of the structural change is highly dependent on the circulation number and the Reynolds number. The fact that the vortex motion is restored at the tail end of the axisymmetric form of breakdown strongly suggests that the phenomenon is a manifestation of critical conditions rather than instabilities. The existence of both the spiral form and the axisymmetric form at very definite conditions of the flow shows that neither one is a consequence of instability in the other

II. DESCRIPTION OF EXPERIMENTAL APPARATUS

The experimental equipment consisted of a plexiglass water tank, a diverging pipe, a reservoir, a rotameter, and the necessary piping and valves. In many ways it was similar to the original equipment used by Reynolds for the demonstration of transition from laminar to turbulent state in non-swirling pipe flows. The plexiglass water tank had the dimensions shown in Figure 1. The bottom was a 62.84 in. x 17.25 in. x 0.75 in. plexiglass plate which was mounted on two metallic I-beams to provide additional support for the structure. All side plates, as well as the cover plate, were 0.70 inches thick. End plates were 13.5 inches wide. Plates were held together by screws and sealed water-tight with commercially available seal material.

One of the end plates (downstream end) had four inlets each of 0.3 inch diameter which were connected through a larger pipe to the supply reservoir.

The other end plate had two small-bore orifices for the passage of dye. One of these holes was drilled just at the center of the plate, the other one being drilled 2.0 inches above it on the same vertical line through the center. Inside the water tank, a second plate was attached to the upstream end plate. A streamlined, solid plexiglass piece, whose diameter was 6.0 inches at its base, was fixed to the inner plate. That piece served two purposes: (a) It was part of the channel which conveyed the fluid to the diverging pipe; (b) It had two small holes --

in correspondence to the small-bore orifices in the plates -- for the injection of dye into the fluid stream. A circular ring, 0.4 inches wide and approximately 7.4 inches inside diameter, was cut into the body of the inner plate. This ring could be rotated in its place by means of a lever attached to both the plate and the ring. Swirl was imparted to the fluid by thirty-two streamlined foils (vanes) symmetrically placed around the inlet piece. Each vane was fixed with one screw to the inner plate. The ring described above had thirty-two small pivots, each one being approximately 1/10 inch long. These pivots were fitted to relatively long slots carved in the edge of each one of the vanes. With this arrangement the vane angle could be changed continuously from zero up to approximately 57 degrees. The dimensions of the vanes and other details are shown in Figures 3 and 4.

As cited above, the streamlined entrance piece attached to the center of the inner plate constituted part of the channel that conveyed the fluid to the diverging pipe. The other wall of the channel was formed by another streamlined piece. It was in turn coupled to the entrance of the diverging tube. This coupling was made in such a manner that there were no protuberances at the junction. The diverging pipe itself constituted the test section for the vortex breakdown. The angle of divergence of the pipe was 1.434 degrees. A round tube (2.0 inches inside diameter) was coupled to the end of the test section. This tube was also connected with a flexible conduit to the inlet of the rotameter. The inside and outside surfaces of both plexiglass tubes and the streamlined entrance pieces were carefully polished and cleaned. The whole arrangement was supported by a trapezoidal plexiglass piece fixed to the bottom of the tank.

The plate covering the water tank had an overflow pipe, as shown in Figures 1 and 2. This provided a constant head in the tank when the fluid was allowed to run out of the overflow pipe. The dye injection tubes (one at the axis and the other 2.0 inches above the axis) were connected to dye reservoirs placed at suitable elevations. The hypodermic tube for the injection of dye at two inches above the axis was made movable longitudinally between the two streamlined entrance pieces in order to inject the dye at various radial distances from the axis or the outer boundary. The maximum displacement of this tube between the walls of the channel was approximately 0.96 inches. This tube could also be rotated, allowing injection of the dye filament parallel to the direction of the local streamlines.

The piping system is shown in Figure 5. After the fluid swirled through the diverging pipe, it passed through the rotameter. The maximum flow rate of the latter was 3.55 gallons per minute. A pressure regulator was installed on the supply line to the reservoir to provide for additional damping of small supply flow fluctuations. The reservoir with its overflow system maintained a constant head.

A mirror (not shown in Figures 1 and 2) covering the total length of the test section and part of the uniform conduit was installed inside the tank. The purpose of this mirror was to show the top side of the vortex breakdown in photographs and motion pictures. The mirror could be set at a convenient angle with respect to the vertical by lowering or raising it with four strings attached to its corners from the outside of the tank.

III. EXPERIMENTAL PROCEDURE

To measure the position of the vortex breakdown along the diverging pipe, a ruler was fixed to the front plate of the test tank. The distance at which the phenomenon occurred was measured relative to the point where the divergence of the tube started. The distances downstream of the said point were considered as positive and vice-versa. To aim at the position of the breakdown more accurately, another ruler, identically equal to the above mentioned, was placed on the opposite side of the tank at the same relative position.

Visualization of the phenomenon was made possible by injecting dye at the center of the stream. The dye flowed by gravity into the tank, thus avoiding any instability in the breakdown which could have possibly been caused by a pressurized dye supply. The density of dye was nearly identical to that of water.

As shown in Figure 6, two sets of data were recorded for the position of the breakdown. The procedure for one of these sets was as follows:

(a) A predetermined value for the flow rate was set in the rotameter;

(b) The vane angle was changed at small steps from zero to 7, 13, 18, 24, 30, 35, 43, 49, 53, and 57 degrees. For this purpose, a pointer was attached to the lever which moved the vanes -- as explained in Section II -- and marks were etched on the plexiglass plate corresponding to each one of the above angles;

(c) After the vortex breakdown had stabilized itself, the distance was recorded by aiming at the two rulers described before;

(d) The flow rate was changed to a new value and steps (b) and (c) repeated. The flow rate was varied from ten percent up to 100 percent of the total flow, in steps of five percent.

To obtain the second set of data, the procedure was changed as follows:

(a) The vane angle was set at a definite value. The accuracy of this setting, as given by the marks on the plexiglass, was checked using a protractor outside the tank;

(b) The flow rate was changed successively, in steps of five percent, from ten percent up to 100 percent of the total flow;

(c) This step was the same for both procedures;

(d) A new angle was set and steps (b) and (c) repeated.

The distances obtained from these procedures were normalized with respect to the inner diameter, D_o, where the test section started to diverge.

A great number of photographs and motion pictures of the phenomenon were taken. Some of them are presented in Figures 7 through 14.

A. EXPERIMENTAL UNCERTAINTIES

The errors in the calculation of the Reynolds number, circulation number, and the position of the vortex breakdown could come from the error in measurements of flow rate, vane angle, measurements of vane dimensions, tube diameter, angle of divergence of the test tube, approximations involved in the calculation of circulation, the energy loss along the streamlined entrance pieces, and the determination of the relative position of the breakdown.

The flow rate was measured with a flowrator calibrated to an accuracy of ±1%. The vane and the test tube dimensions were machined to an accuracy of approximately 1.5%. The calculation of the circulation may yield an error of approximately 5%. The location of the vortex breakdown may be regarded as accurate to within 7%. This depended on the type of the breakdown. For axisymmetric breakdown this accuracy was estimated at 4%. The location of the spiralling breakdown is not as stable as that of the axisymmetric breakdown and thus there is no accurate way of attaching a measure of experimental uncertainty.

A simple application of the matters of Kline and McClintock (16) to the quantities which varied through the experiment has shown that for the data presented herein the uncertainty was about 5% for the axisymmetric breakdown and about 7% for the spiralling vortex breakdown. It must, however, be pointed out that the purpose of this investigation was not to secure engineering design data but rather to explore the basic mechanism of the vortex breakdown.

IV. PRESENTATION AND DISCUSSION OF RESULTS

The arrangement of the vanes, as explained before, allowed a wide range of variation of the vane angle. Some discrete angles were selected to perform the experiments and the flow was observed at each vane setting.

The behavior of the flow field as both the vane angle and the flow rate were changed is described in the following discussion. It is convenient to review first the parameters in which the discussion is presented.

A careful analysis of the parameters affecting the phenomenon shows that the location and the type of vortex breakdown are functions of three independently variable parameters. These are the circulation number W, the Reynolds number Re, and the angle of divergence of the test tube. In the present study one test tube was used. Thus the location and the type of breakdown were uniquely determined by the circulation and the Reynolds numbers.

The Reynolds number was based on the average, uniform axial velocity U, at the entrance to the diverging tube. The inside diameter, D_o, at the entrance of the tube, was chosen as the characteristic length. Therefore, the Reynolds number was expressed as

$$Re = \frac{U D_o}{\nu} \tag{1}$$

After substituting the value for U, the final expression became

$$Re = \frac{4 \sigma Q_m}{\pi \nu D_o} \qquad (2)$$

where Q_m is the maximum flow rate through the rotameter and σ is a multiplication factor which accounts for the percentage of the maximum flow rate.

The remaining parameter, the circulation number, was calculated as follows (see Figure 3): the passage between the vanes was a duct of rectangular, constant cross-section for a given vane angle. The area of the duct was given by the product of the dimensions H and z. The constant dimension H was the length (perpendicular to the plane of Fig. 3) between the two streamlined entrance pieces, its value was 1.0625 inches. The distance between adjacent vanes, z, is given by

$$z = 2\ b \cos \phi - \frac{\pi \alpha}{90} \quad 1 \qquad (3)$$

The circumferential component of velocity of the incoming fluid is given given by $V_1 \sin \eta$, as shown in Figure 3. The amount of circulation imparted to the fluid thus reduces to:

$$\Gamma = 2 \pi R\ (32)\ V_1 \sin \eta \qquad (4)$$

Since

$$V_1 = \frac{Q}{32\ z\ H} \qquad (5)$$

circulation becomes

$$\Gamma = \frac{2\ \pi R\ Q}{z\ H} \sin \eta \qquad (6)$$

where η is given by (see Figure 3)

$$\eta = \tan^{-1} \frac{\sin \phi}{\cos \phi - 1/R} \tag{7}$$

The final relation for the circulation number reduces to

$$W = \frac{\Gamma}{U\, D_o} = \frac{R\, D_o\, \pi^2}{2\, z\, H} \sin \eta \tag{8}$$

The values for σ, U, Re, Q, and the product $z\, V_t$, are presented in Table I. Those for ϕ, η, z, and W, are presented in Table II.

The vortex breakdown, in its two well-known types, did not exist for values of W between 17.6 and 33.8. In this range, for values of Reynolds number greater than 5200, a periodic wavy motion was originated in the region near the outlet of the diverging tube. The dye filament transformed into a turbulent motion immediately downstream of the waves. The periodic motion was very unstable. The wave appeared occasionally near mid-length of the tube and moved rapidly to the downstream end. It it believed that this could very well be the behavior of the flow at an incipient state of the spiral type of breakdown. Perhaps at a Reynolds number greater than 8100 (which was, approximately, the maximum value for the present experiment) the spiral breakdown could be detected.

The breakdown phenomenon was observed to occur for circulation numbers greater than 44.0. The normalized positions of the breakdown versus Reynolds number are shown in Figure 6 for constant values of W.

At W = 44.0 a very mild spiral breakdown existed for Re > 5200. The behavior of the flow was somewhat like that described for W < 33.8 yet the characteristic spiral could be observed. There were no waves originating at mid-length of the diverging tube. However, small waves were sometimes observed just upstream of the point where the vortex core had deviated from the straight-line direction. This caused a disorderly motion of the spiral and, on occasions, the spiral almost disappeared yielding to turbulent motion. This instability was also observed for the spiral breakdown at W = 53.5, the only difference being that at high Reynolds numbers the spiral moved a short distance upstream. Then at some point, the vortex core fanned out originating a structure resembling a wine cup or tulip, as it has been called by other authors. This does not necessarily mean that the axisymmetric form of breakdown is a consequence of instabilities of the spiral form, inasmuch as the "tulip" went promptly downstream and the original spiral was restored.

The origin of the small waves which caused the said disturbances is unknown. Perhaps they could be the result of small supply flow fluctuations. In any case, they pose a question on Benjamin's theory of conjugate flows, where the primary flow cannot support standing waves. Hall (17), in his thorough study on vortex cores, suggests that Benjamin's supercritical flow may be unstable to spiral disturbances. Since the primary flow must be close to the stability boundary for axisymmetric disturbances, he suggested that perhaps it is necessary to consider spiral disturbances in a theory for infinitesimal transitions.

It is interesting to note that in past experiments in vortex tubes the stagnant bubble, typical of the axisymmetric form of breakdown, has been almost exclusively observed. In the present investigation it has been shown that the spiral form may exist as an unsteady but consistently controllable phenomenon in tube flow. The sense of the spiral, as the dye filament was thrown out of the axial line, was in the same direction of rotation as that of the upstream flow. An eccentric dye filament had also the same direction of motion. This did not agree with the observations of Lambourne and Bryer (3) and Lowson (18), regarding the flow over a wing. They reported that the sense of the spiral was in the opposite direction to the rotation of the fluid elements upstream, while an eccentric dye filament behaved as described above. Hall (17), based on the observations of Lambourne and Bryer, as well as Lowson's, concluded that the flow over a wing could not be axisymmetric. Therefore, following Hall's criterion, it must be concluded that the vortex tube flow is indeed axially symmetric.

The normalized positions of breakdown shown in Fig. 6 for W = 44.0 are somewhat approximate. The instabilities described above, as well as a continuous shifting of the spiral over short distances upstream and downstream, made the task of recording the position of breakdown a rather difficult one. This is the main reason for the differences observed in Fig. 6 for both sets of data points.

At W = 53.5 the spiral breakdown was stronger than that at W = 44.0. The stagnation point at the axis of the vortex core (where the spiral arose) was well defined. The said point, for W = 44.0, was not too distinct. At low values of W, mild spiral vortex breakdown may be expected, while at greater values the spiral will become stronger and more stable. Finally, at higher values of W, the egg-shaped axisymetric structure will appear almost exclusively for any value of the Reynolds number.

The position of the spiral, i.e., the point of stagnation, at W = 53.5, moved both upstream and downstream for some distance. This distance, for a given value of Reynolds number, was not constant with time. Therefore, an approximate average position was recorded and plotted in Figure 6. The influence of Reynolds number on the position of the breakdown, for W = 53.5, was not too great compared to that for W $\geq$ 73.9 This can be deduced from the curves shown in Figure 6.

Some photographs of the spiral breakdown are shown in Figures 7, 8, and 9.

The spiral form of the vortex breakdown phenomenon persisted at W = 73.9 for low values of the Reynolds number. In this case the spiral was as strong as that for W = 53.5 yet the movement about the most stable position was very small. No waves were observed upstream of the spiral form. As the Reynolds number was increased the axisymmetric form of the breakdown developed. The phenomenon created an egg-shaped structure having a core of reversed flow. At the upstream end of the bubble the vortex core expanded and the dye traced the exterior surface of the structure. At the downstream end, at short radial distance from the axial line, the flow reversed its direction of motion completely. At the same time, the vortex motion was restored at the tail end of the bubble. The core of this vortex was thicker than that of the original upstream vortex. A second, well-defined breakdown, developed at some distance downstream, the phenomenon now being of the spiral type. The flow became turbulent further downstream, (see Figure 13).

Most of the fluid which reversed its direction of motion remained trapped inside the axisymmetric bubble. This was shown by cutting the supply of dye and recording the time it took the colored fluid to disappear. Periods of time of as long as 20 seconds were recorded for the values of parameters encountered herein.

Increasing the dye supply it was observed that the streamlines a short distance away from the exterior surface of the egg-shell were forced to flow around the latter, without showing any reversed motion. As the distance increased, the presence of the swirling laminar flow was observed. This was also observed in the dye filament injected away from the axis of the core. The vortex flow became turbulent downstream, as a consequence of the turbulence originated from the breakdown.

The axisymmetric type of breakdown is shown in Figures 10, 11, and 12.

Figure 10 shows the tail end of the bubble almost closed and the laminar vortex flow around the breakdown.

In Figure 11 the dye supply has been almost completely cut. The colored fluid in the axisymmetric body, however, has not been washed away, as one might have otherwise expected.

The photograph shown in Fig. 12 was taken using a dye of different color. This allowed the observation inside the body. The reversal of the flow direction is quite clear in this Figure. A filament resembling a spiral is also observed inside the bubble. This filament suggested that the vortex motion tried to restore itself within the bubble. However, proof of this was not obtained.

The restoring of the vortex motion at the tail end of the bubble supports the idea that the axisymmetric breakdown is a sudden change between two states of flow rather than a consequence of instabilities. In fluid flow the concept of "instability" would suppose the existence of some condition which would produce a disorganized change of structure which will grow indefinitely with time. In axisymmetric breakdown the immediate upstream and downstream flow conditions are similar in character and far from being turbulent.

The fact that the second breakdown is spiraled suggests that the deceleration experienced by the flow induces a lower Reynolds number, as well as a lower circulation number, downstream of the axisymmetric structure.

The dependence of the phenomenon on Reynolds number is clearly demonstrated from the examination of the curves for W = 73.9 and greater.

At W = 73.9 the position of the breakdown varied over a wide range when Reynolds number was changed from approximately 800 up to 6000. At higher Reynolds number, its influence on the position was diminished.

In general, the axisymmetric form of breakdown maintained nearly a constant position for a given Reynolds number and circulation number. On occasions the bubble drifted a very small distance either upstream or downstream yet the motion always came to an end at the same point where it was started.

At both W = 96.5 and W = 118.8 the behavior of the breakdown, in its two types, was the same as that described for W = 73.9.

At W = 96.5, for values of Re greater than 4000, the breakdown moved up to the outlet of the hypodermic tube through which the dye was injected and the flow became turbulent immediately at that point. Further increase in Reynolds number caused the dye to stick to the wall of the streamlined entrance piece. The same feature was observed at W = 118.8 for Reynolds number greater than 2400.

The curves shown in Fig. 6 provide a clear understanding of the effect of circulation number on the position of vortex breakdown.

As the circulation number is increased the position of the breakdown moves upstream and vice-versa.

For a circulation number equal to 152.7, the highest investigated, the phenomenon occurred too close to the entrance of the diverging tube. With a slight increase in Reynolds number a region of turbulent mixing developed near the streamlined entrance piece.

An interesting difference between the present investigation and that of Harvey's (11), was his observation of a central core region of reversed flow which filled the whole length of his test tube. This did not occur, at any moment, during the course of the present experiment. Harvey's experiment was conducted at an approximately constant Reynolds number (which was about 1.4×10^5 for the configuration of his apparatus). However, he did not report at what setting of vane angle the central core region appeared. Therefore, no explanation can be offered for that difference between his and the present experiment.

A structure resembling the double helix pattern reported by McHugh (1) was also observed. The said structure appeared at a low value of Re and W = 73.9. It only lasted a few seconds, the time enough to take a photograph of the phenomenon. This photograph is shown in Fig. 14.

In an attempt to isolate the double helix pattern, another feature of the vortex breakdown was observed: By increasing the Reynolds number (at W = 73.9) at an unusually slow rate, the spiral type of breakdown could be maintained up to Re = 4000. This suggested the existence of an overlapping region ($3200 < Re < 4000$), where the axisymmetric form of breakdown was precipitated by a reasonable rate of increase of the Reynolds number.

An attempt was made to measure the swirl angle of the flow upstream of breakdown. The dye filament injected away from the axis of the vortex core was used to accomplish this purpose. However, the obtained results did not have the desired accuracy. Therefore, the results are not presented in this thesis. Some modifications to the experimental apparatus should give better results for the value of the swirl angle and its relation to the vortex breakdown phenomenon.

V. CONCLUSIONS

1. Vortex breakdown is highly dependent on the circulation number. The influence of this parameter is two-fold, because it affects the position, as well as the structure of the phenomenon. At low values of circulation number the spiral form of breakdown dominates over a wide range of Reynolds numbers. Its position is located an appreciable distance downstream in the test section. At higher values of circulation number the breakdown is mostly of the axisymmetric type. The position where breakdown occurs is nearer the entrance of the test section.

2. The position of the vortex breakdown is also determined, within some limits, by the Reynolds number. There appears to be a relationship between the effects of both the Reynolds number and circulation number on the position of the breakdown. At low values of circulation number the influence of Reynolds number is not too strong, yet the breakdown moves upstream as Reynolds number increases. At high values of circulation number the rate of upstream displacement of the breakdown, as Reynolds number is increased, is rather high. However, as the Reynolds number reaches higher values its influence on the position of breakdown diminishes.

3. The vortex breakdown phenomenon appears to be a manifestation of critical conditions rather than instabilities. This is suggested by the restoring of the vortex motion at the tail end of the axisymmetric form of breakdown.

4. The existence of both the spiral form and the axisymmetric form at very definite conditions of the flow has shown that neither one is a consequence of instability in the other.

TABLE I

Percentage of Q_m σ (%)	Uniform Axial Velocity U (ft/sec)	Reynolds Number Re	Actual Flow Rate Q (ft^3/sec)	Entrance Velocity at Vanes * zV_i (ft/sec)
10	0.0645	806	0.000792	0.000279
15	0.0968	1209	0.001188	0.000419
20	0.1290	1612	0.001583	0.000558
25	0.1614	2015	0.001980	0.000698
30	0.1938	2418	0.002375	0.000837
35	0.2260	2821	0.002771	0.000976
40	0.2580	3224	0.003169	0.001118
45	0.2905	3627	0.003563	0.001258
50	0.3230	4030	0.003960	0.001397
55	0.3550	4433	0.004360	0.001536
60	0.3860	4836	0.004750	0.001676
65	0.4200	5239	0.005150	0.001816
70	0.4520	5642	0.005545	0.001955
75	0.4840	6045	0.005940	0.002094
80	0.5160	6448	0.006340	0.002234
85	0.5490	6851	0.006740	0.002373
90	0.5810	7254	0.007130	0.002513
95	0.6130	7657	0.007525	0.002652
100	0.6450	8060	0.007920	0.002790

* Column five gives the product of the entrance velocity at the vanes times the effective distance between adjacent vanes

TABLE II

Vane Angle (degrees) ϕ	Trailing Edge Angle η (degrees)	Effective Distance Between Vanes z (feet)	Circulation Number W
7	10.3	0.0462	9.4
13	19.0	0.0449	17.6
18	26.2	0.0433	24.7
24	34.5	0.0407	33.8
30	42.6	0.0374	44.0
35	49.0	0.0343	53.5
43	59.0	0.0282	73.9
49	66.1	0.0230	96.5
53	70.6	0.0193	118.8
57	75.1	0.0154	152.7

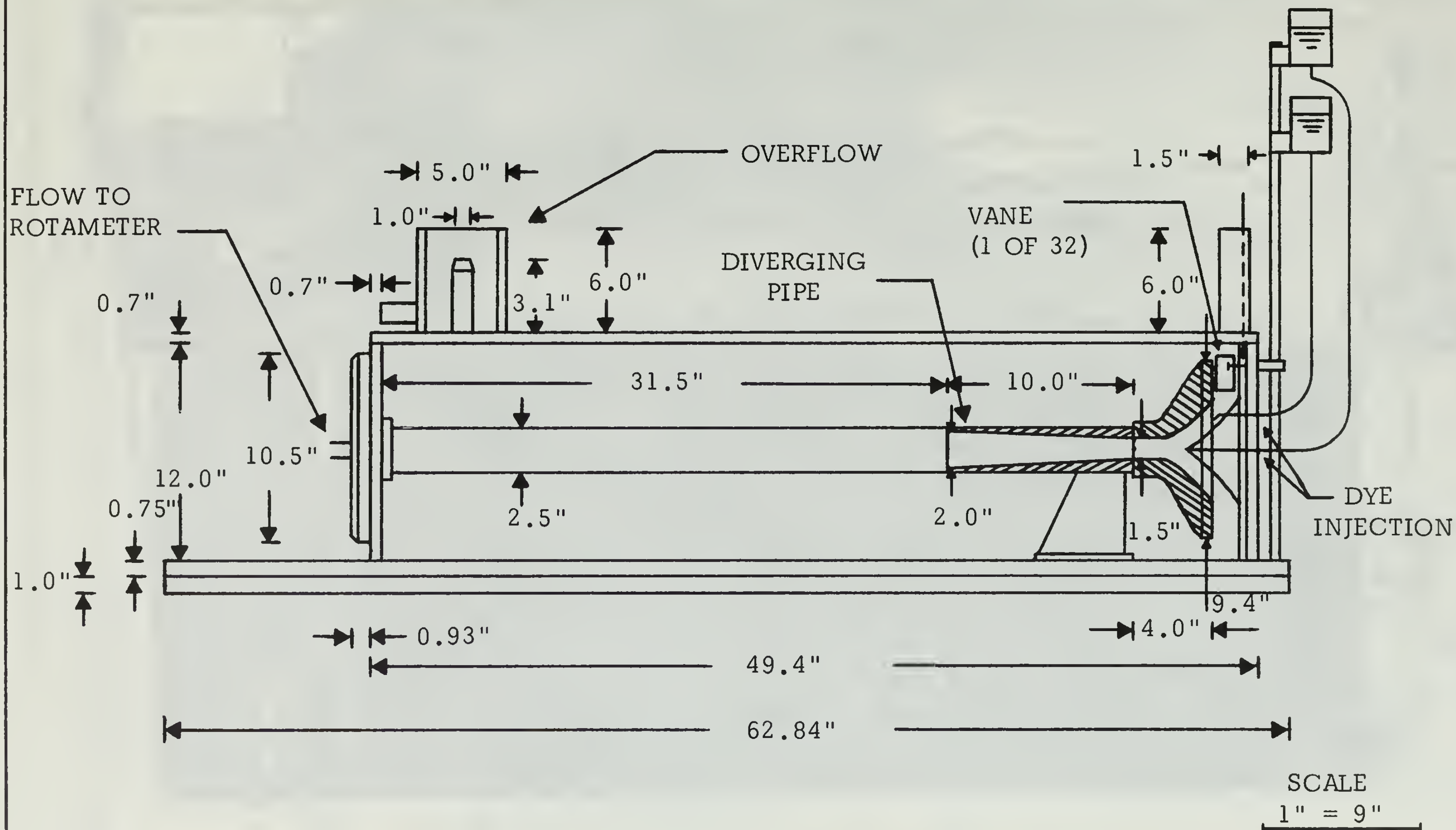


FIG. 1. SCALE DRAWING OF TEST APPARATUS

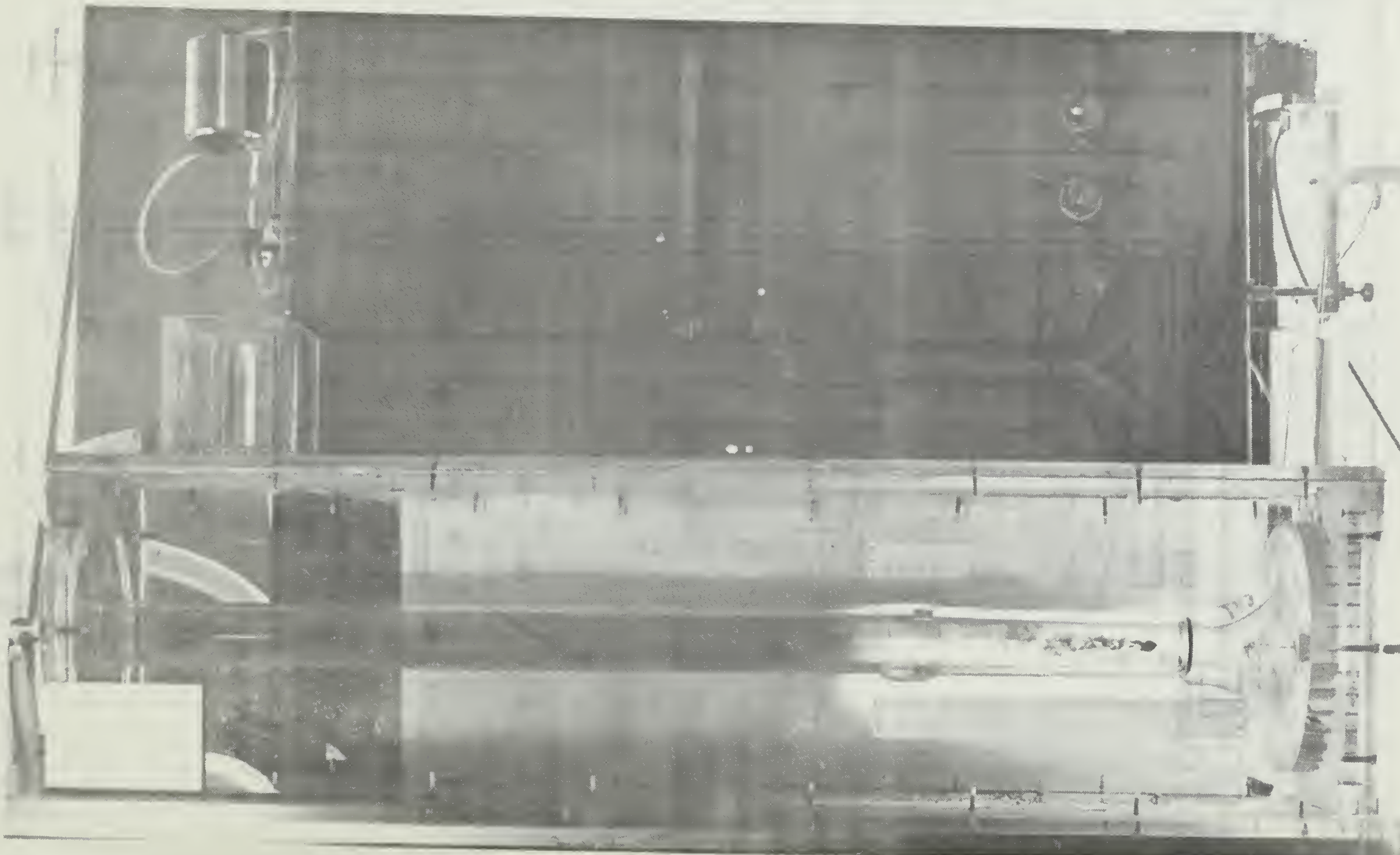
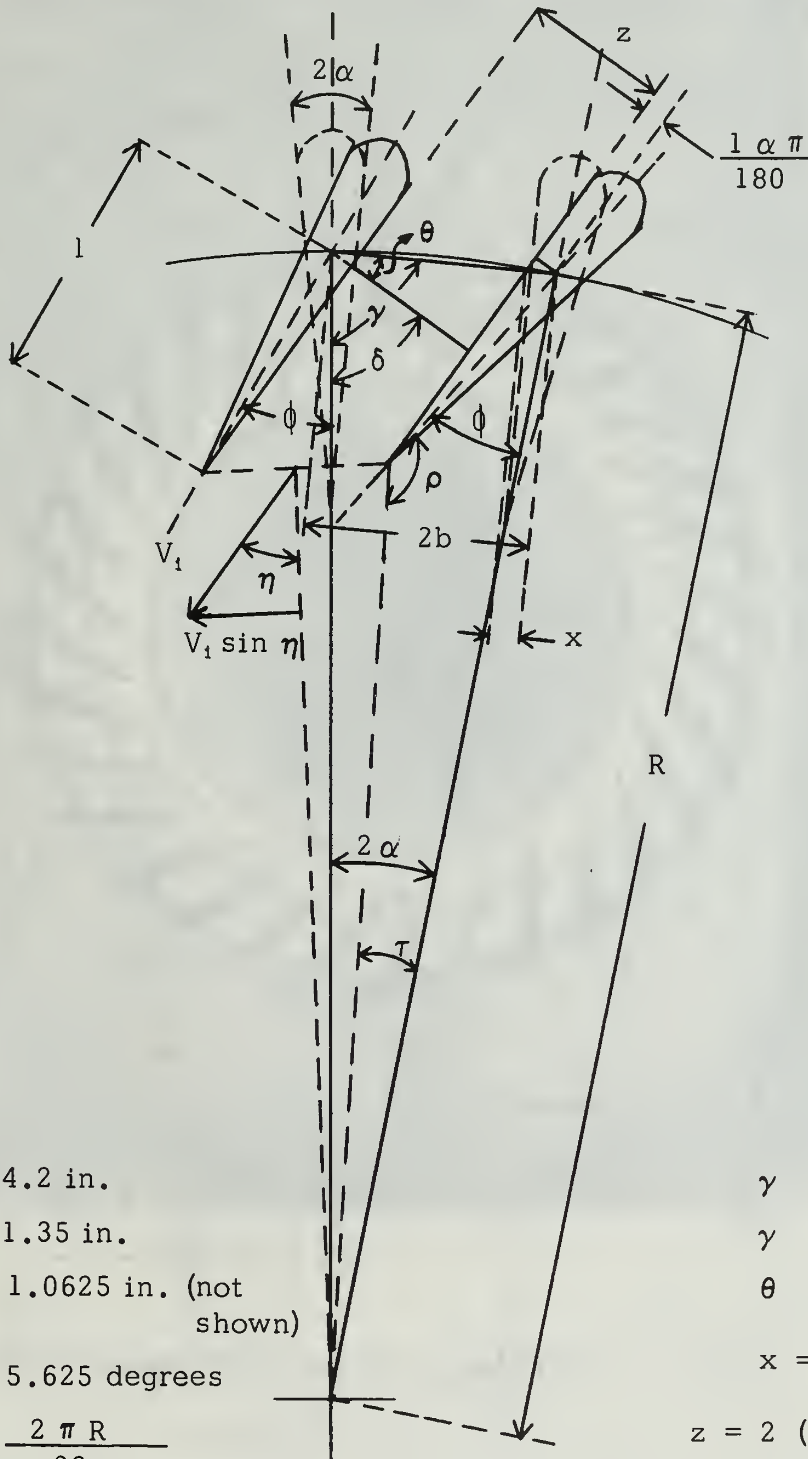


FIG. 2. TEST TANK AND DIVERGING PIPE (FRONT SIDE)



R = 4.2 in.

1 = 1.35 in.

H = 1.0625 in. (not shown)

α = 5.625 degrees

$$2b = \frac{2\pi R}{32}$$

$\gamma = \delta + \theta$

$\gamma = \delta + \phi$

$\theta = \phi$

$$x = \frac{1\ \alpha\ \pi}{180 \cos \theta}$$

$$z = 2\ (b - x) \cos \theta$$

FIG. 3. DIMENSIONS OF VANE AND DEFINITION OF VANE ANGLE

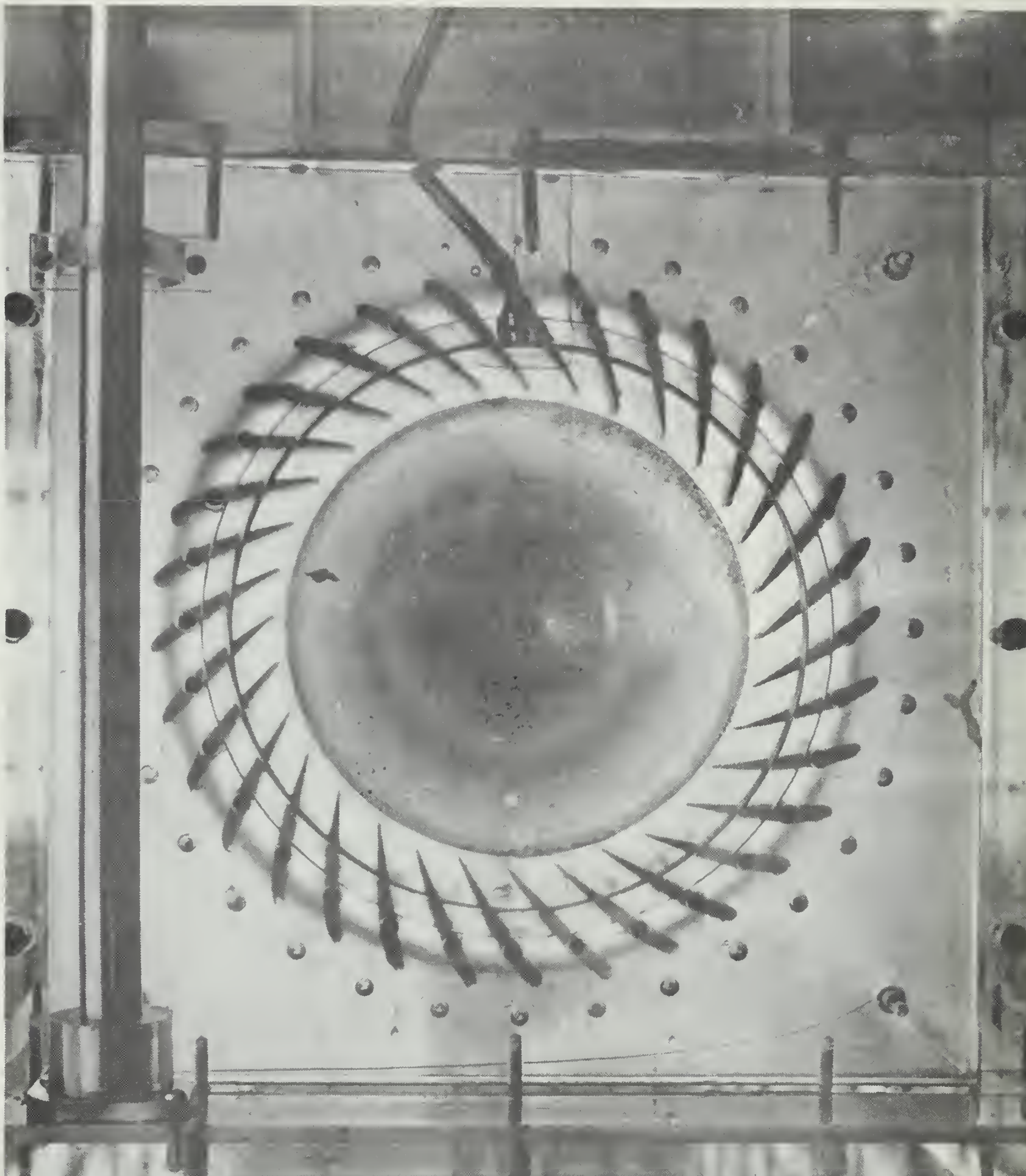


FIG. 4. UPSTREAM PLATE AND VANE ARRANGEMENT

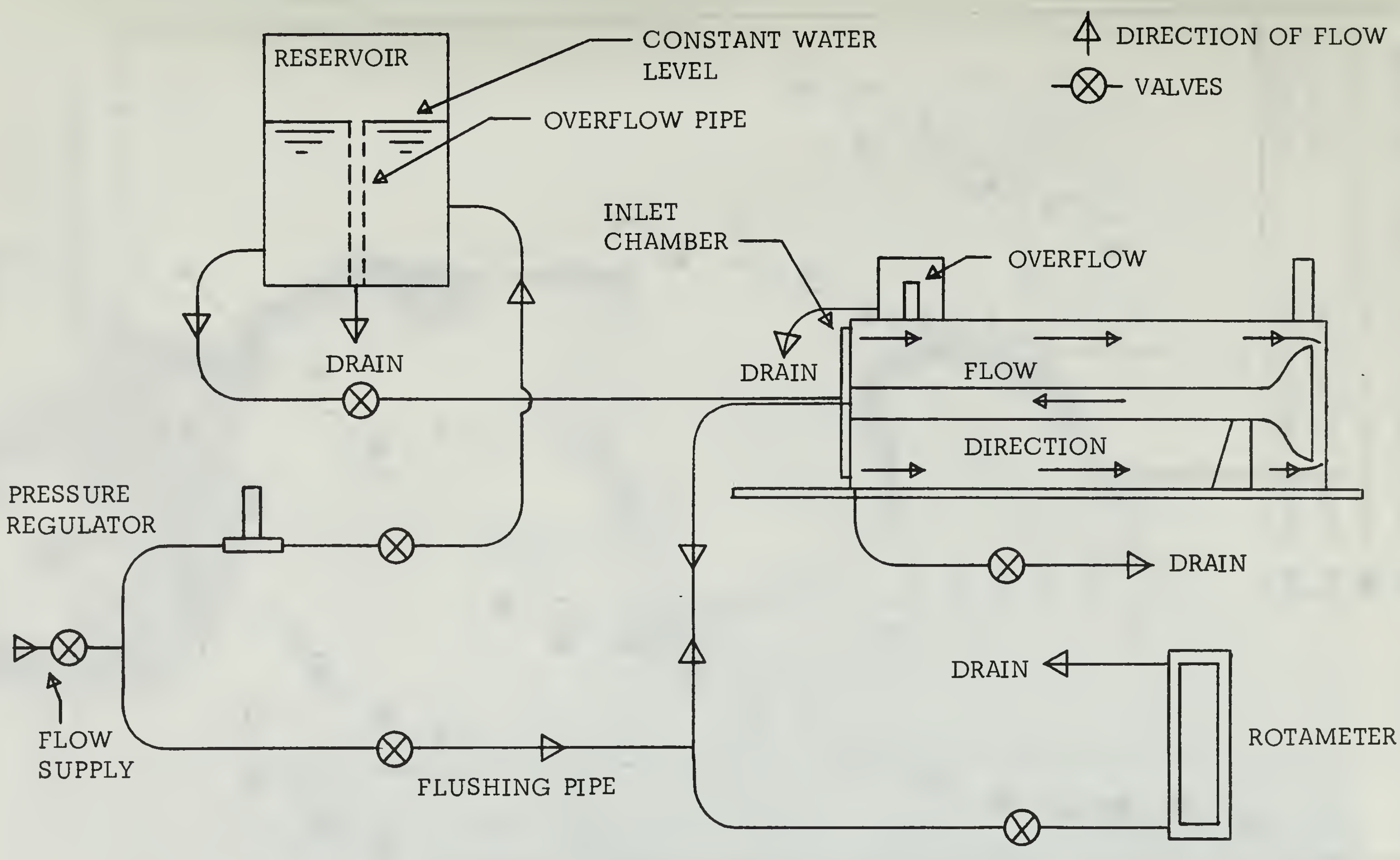


FIG. 5. ARRANGEMENT OF THE FLOW SYSTEM

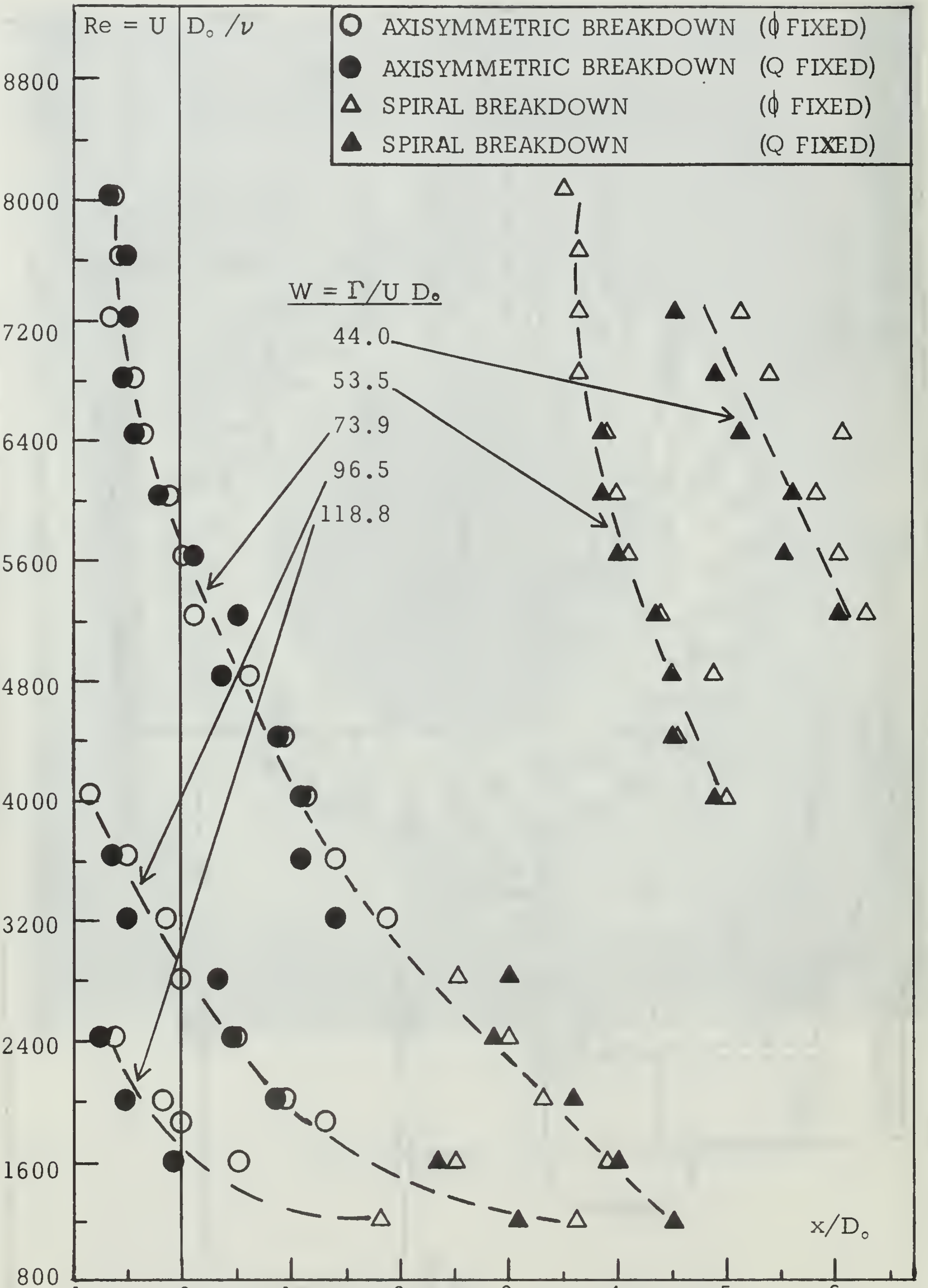


FIG. 6. NORMALIZED POSITION OF VORTEX BREAKDOWN VERSUS Re NUMBER

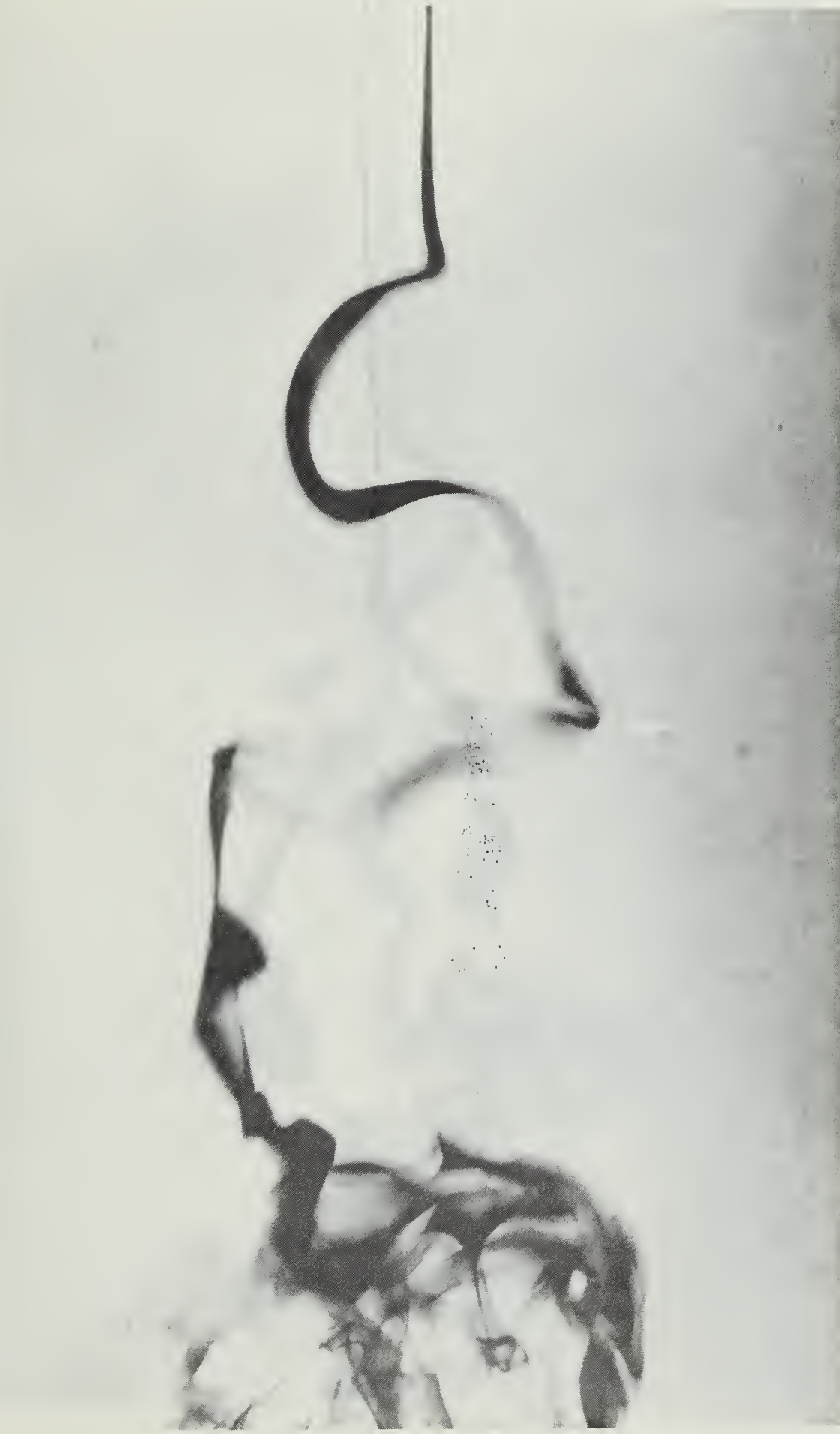


FIG. 7. EXAMPLE OF SPIRAL VORTEX BREAKDOWN

FIG. 8. EXAMPLE OF SPIRAL VORTEX BREAKDOWN

FIG. 9. EXAMPLE OF SPIRAL VORTEX BREAKDOWN

FIG. 10. EXAMPLE OF AXISYMMETRIC VORTEX BREAKDOWN

FIG. 11. EXAMPLE OF AXISYMMETRIC VORTEX BREAKDOWN

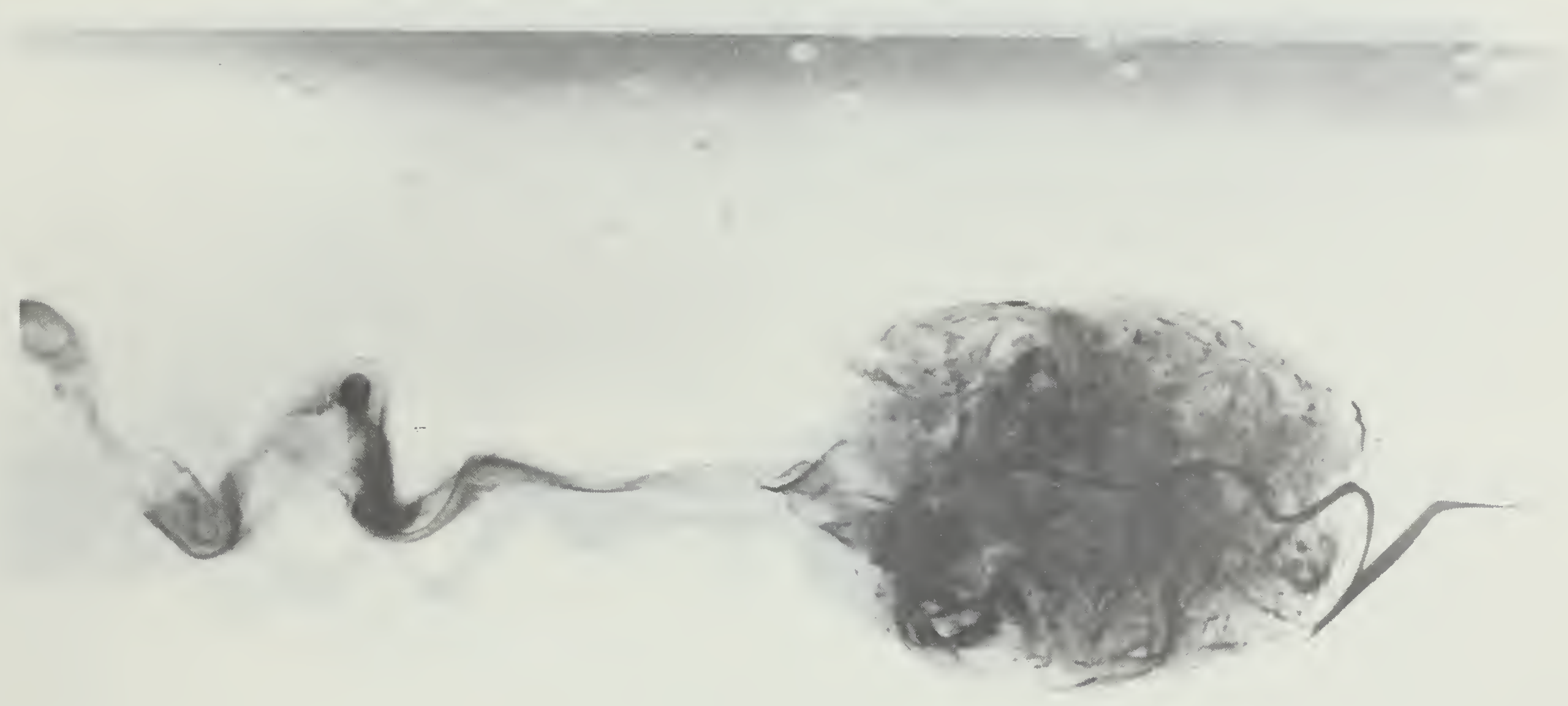


FIG. 12. EXAMPLE OF AXISYMMETRIC VORTEX BREAKDOWN

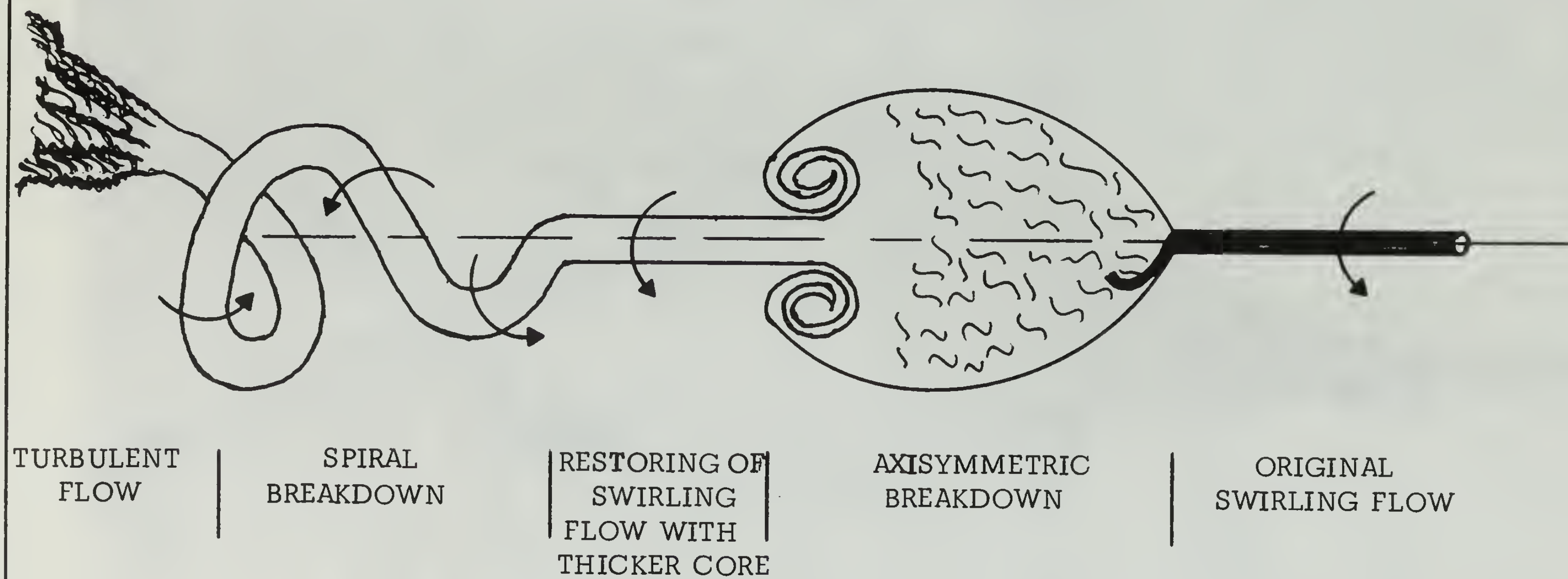


FIG. 13. SKETCH OF THE AXISYMMETRIC VORTEX BREAKDOWN

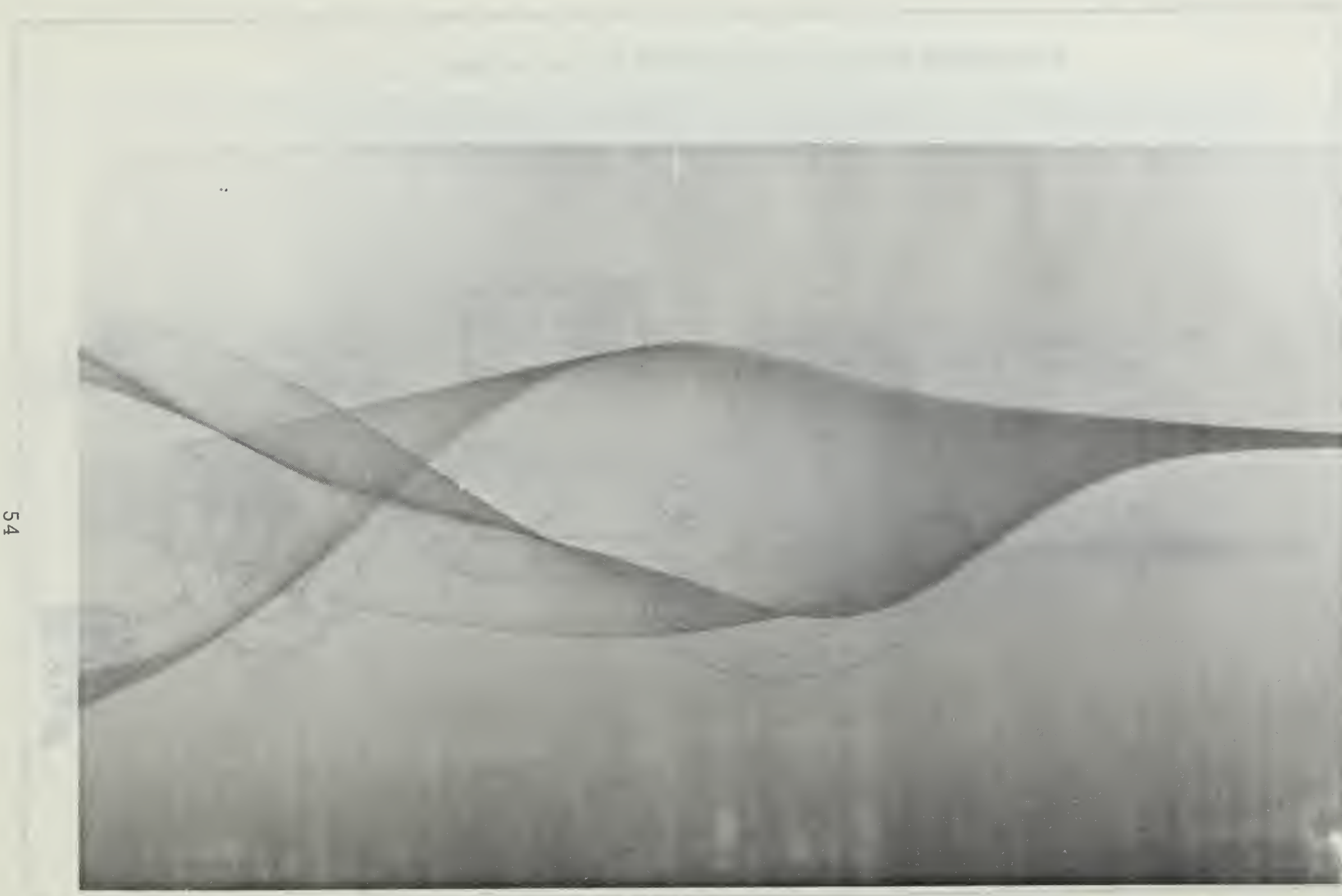


FIG. 14. EXAMPLE OF HELICAL VORTEX BREAKDOWN

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13. ABSTRACT

The vortex breakdown phenomenon was investigated, through the use of flow visualization techniques, over a wide range of flow conditions in terms of the circulation number and the Reynolds number.

The test section of the apparatus was, basically, a 10-inch diverging tube whose inside diameter was changed uniformly from 1.5 inches to 2.0 inches. The swirling flow was generated by introducing water through an arrangement of 32, radially located, streamlined vanes. The vortex breakdown position was recorded for different values of both the circulation number and the Reynolds number.

The results of the investigation have shown that the vortex breakdown may occur either in spiral or axisymmetric form (followed by a thicker core, then a spiral breakdown) and finally by turbulent mixing. The character of the structural change, as well as the position of the breakdown along the tube, are highly dependent on the circulation number and the Reynolds number. The existence of both types of breakdowns at well defined flow conditions shows that neither one is a consequence of instability in the other. The phenomenon appears to be a manifestation of critical conditions rather than flow instabilities.

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